Physica C 484 (2013) 159–162

Contents lists available at SciVerse ScienceDirect

Physica C

journal homepage: www.elsevier.com/locate/physc

Anisotropic thermal transport in Bi2223/Ag superconducting tape with sandwiched structure

Tomoyuki Naito [a,b,*], Hiroyuki Fujishiro [a,b], Goro Osabe [c], Jun Fujikami [c]

[a] Department of Materials Science and Engineering, Faculty of Engineering, Iwate University, Morioka 020-8551, Japan
[b] Soft-Path Engineering Research Center (SPERC), Faculty of Engineering, Iwate University, Morioka 020-8551, Japan
[c] Sumitomo Electric Industries Ltd., Osaka 554-0024, Japan

ARTICLE INFO

Article history:
Accepted 19 March 2012
Available online 28 March 2012

Keywords:
Bi2223/Ag tape
Thermal conductivity
Anisotropy
Equivalent heat current circuit

ABSTRACT

The thermal conductivity, $\kappa(T)$, of the Bi2223/Ag tape reinforced by metal tapes (stainless steel (SS) or copper-based alloy (CA)) from both side was evaluated along the length (l) and width (w) directions. $\kappa(T)$ along the l-direction was measured directly using a single tape and that along the w-direction was estimated from the $\kappa(T)$ measured for a stacked bundle which consists of several sandwiched Bi2223/Ag tapes. We analyzed the obtained $\kappa(T)$ curves using an equivalent heat current circuit, and found that the heat transports along both directions were nearly the same and that the route of heat-flow depended on the species of the reinforcing metal. The absolute values of $\kappa(T)$ at 77 K along the l- and w-directions for the Bi2223/Ag-SS tape were 174 and 140 W m^{-1} K^{-1} and those for the Bi2223/Ag-CA tape were 206 and 206 W m^{-1} K^{-1}, respectively, the values of which were approximately 30–40% and 10–15% smaller than those of the standard Bi2223/Ag tape.

1. Introduction

Recently, the critical current, I_c, of a superconductive Bi2223 sheathed with silver (Bi2223/Ag) tape exceeded 200 A at 77 K under the self-field [1]. Therefore, the Bi2223/Ag tapes are promising materials to fabricate the coil, transformer and so on. Thermal conductivity, $\kappa(T)$, is one of the important physical properties for the estimation of the thermal stability for the superconducting applications. We have measured the $\kappa(T)$ of various Bi2223/Ag tapes [2–4]. Recently, we reported $\kappa(T)$ of the Bi2223/Ag tape along three typical directions, the length (l), width (w) and thickness (t) [5]. The $\kappa(T)$ values along the l- and w-directions were almost identical with each other and the heat flew mainly through the Ag sheath. On the other hand, the magnitude of $\kappa(T)$ along the t-direction was about one order of magnitude smaller than those along other directions, because of the small cross section of Ag path. In addition to the thermal stability for the applications, it is necessary to enhance the mechanical strength of the Bi2223/Ag tapes. To achieve higher mechanical strength, the Bi2223/Ag tape is usually sandwiched by thin metal tapes, such as stainless steel, brass, bronze and so on. In this case, $\kappa(T)$ of the sandwiched Bi2223/Ag tape along the l-direction depends on the species and thickness of the reinforcing metal tape [4]. However, the anisotropic $\kappa(T)$ of the Bi2223/Ag tape with sandwiched structure had not been investigated.

In this paper, we measured the $\kappa(T)$ of the Bi2223/Ag tape with sandwiched structure along the l-direction and estimated $\kappa(T)$ along the w-direction from the $\kappa(T)$ measured for the stacked bundle which consists of several sandwiched Bi2223/Ag tapes. The anisotropic heat flow in the Bi2223/Ag tape with sandwiched structure is discussed using an equivalent heat current circuit.

2. Experimental procedure

2.1. Sample preparation

Bi2223/Ag tapes were fabricated by the powder in tube (PIT) method with the controlled overpressure (CT-OP) sintering technique at Sumitomo Electric Industries, Ltd. The details of the fabricating process was described elsewhere [6]. A standard Bi2223/Ag tape (Type H) reinforced by sandwiching from both surfaces using thin metal tapes and the solder (LFM-48) was named Type HT. In this study, two Type HT tapes reinforced by stainless steel (SS) 20 μm in thickness or the copper-based alloy (CA) 50 μm in thickness were prepared and named Types HT-SS or HT-CA, respectively.

As shown in Fig. 1a, $\kappa(T)$ along the l-direction was measured directly using the single Type HT tape, which was abbreviated as the l-sample. $\kappa(T)$ along the w-direction was estimated from the measured $\kappa(T)$ of the stacked bundle. The bundle, which was named w-sample, was prepared by joining several Type HT tapes

* Corresponding author at: Department of Materials Science and Engineering, Faculty of Engineering, Iwate University, Morioka 020-8551, Japan. Tel./fax: +81 19 621 6362.
E-mail address: tnaito@iwate-u.ac.jp (T. Naito).

0921-4534/$ - see front matter © 2012 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.physc.2012.03.043

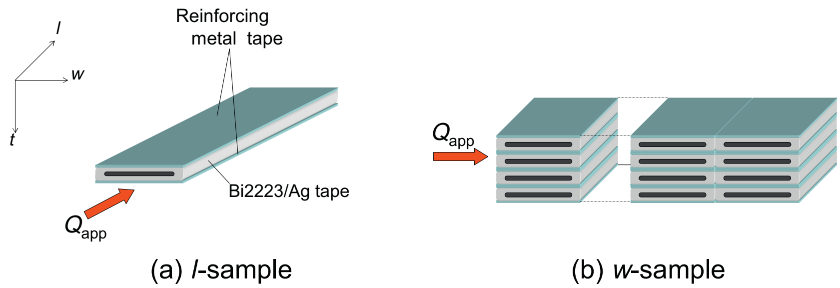

Fig. 1. Schematic illustration of (a) the single Bi2223/Ag tape with sandwiched structure for the measurement of the thermal conductivity, $\kappa(T)$, along the length direction (*l*-sample) and (b) the stacked bundle for the estimation of $\kappa(T)$ of the tape along the width direction (*w*-sample).

using the solder (LFM-48), as described in Fig. 1b. As reported previously [5], the thermal contact resistance at the solder layer between the Bi2223/Ag tapes in the *w*-sample can be ignored. Therefore, we regard the measured $\kappa(T)$ of the *w*-sample as $\kappa(T)$ along the *w*-direction.

2.2. Thermal conductivity measurement

Thermal conductivity, $\kappa(T)$, was measured by a steady-state heat flow method. One end of the sample was thermally attached to a heat sink. A small metal chip resistor (1 kΩ) was adhered to the other end of the sample as a heater using GE7031 varnish. A constant current was applied to the heater, and then the constant temperature gradient, grad *T*, was measured. κ is given as $\kappa = q/\mathrm{grad}\,T$, where *q* is the heat flux per unit cross section and grad *T* is given by the temperature difference ΔT divided by the distance *L* between the two thermocouples. The temperature of the sample was controlled using a Gifford–McMahon cycle refrigerator and 30 W heater. To eliminate radiation loss, κ was measured below 200 K.

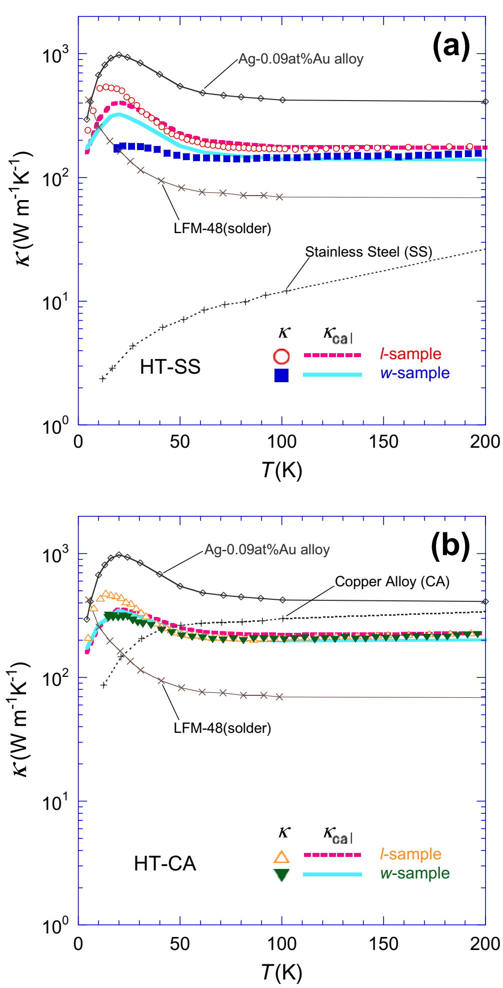

Fig. 2. Temperature dependence of the thermal conductivity, $\kappa(T)$, of the length (*l*) and width (*w*) samples for (a) Type HT-SS and (b) Type HT-CA. The thick lines represent the calculated thermal conductivities $\kappa_{cal}(T)$ (see text). The reported $\kappa(T)$ curve of Ag–0.09 at%Au alloy [7] and the measured $\kappa(T)$ curves of the solder (LFM-48), the stainless steel (SS) tape 20 μm in thickness and the copper-based alloy (CA) tape 50 μm in thickness are also shown.

3. Results

Fig. 2a and b shows the temperature dependence of the thermal conductivity, $\kappa(T)$, of the Types HT-SS and HT-CA samples, respectively. $\kappa(T)$ reported for Ag–0.09 at%Au alloy [7] and $\kappa(T)$'s measured for the solder (LFM-48), the SS tape and the CA tape are also shown. $\kappa(T)$ of the *l*-samples for both HT-SS and HT-CA slightly decreases with decreasing temperature, starts to increase below 70 K, and takes a maximum of about 500–550 W m^{-1} K^{-1} around 14 K. Absolute value and temperature dependence of $\kappa(T)$ depend on the species of the reinforcing material. $\kappa(T)$ of the *w*-sample for Type HT-SS somewhat rapidly decreases with decreasing temperature and deviates from $\kappa(T)$ of the *l*-sample. The peak in $\kappa(T)$ of the *w*-sample is suppressed to one third of that of the *l*-sample. For Type HT-CA, $\kappa(T)$ of the *w*-sample almost corresponds to that of the *l*-sample from 200 K down to 40 K. Its maximum appeared below 20 K is about half of that of the *l*-sample.

4. Discussion

To clarify the anisotropic heat transport in the Type HT tapes, we examine the contribution of each constitutional part to the heat transport. An equivalent heat current circuit is considered in the following procedure. When the applied heat, *Q*, flows in the Bi2223/Ag tape sandwiched by metal tapes, *Q* is given as

$$Q = Q_s + Q_m + Q_{\mathrm{sol}},$$

where, Q_s, Q_m and Q_{sol} are the heat flow through the Bi2223/Ag, metal tape and solder layer, respectively. Since the ΔT and *L* are the same for all the parts, the total thermal conductivity, κ_{tot}, can be estimated by

$$\kappa_{\mathrm{tot}} = \frac{\kappa_s \times S_s + \kappa_m \times S_m + \kappa_{\mathrm{sol}} \times S_{\mathrm{sol}}}{S_{\mathrm{tot}}},$$

where, κ_s, κ_m and κ_{sol} are the thermal conductivities and S_s, S_m and S_{sol} are the cross sections for each part. As schematically shown in the left of Fig. 3a, the Bi2223 filaments distribute finely in the Ag sheath, which complicates the route of the heat current. To simplify the equivalent heat current circuit, we virtually collected the Bi2223 parts at the center of the cross section as shown in the right of Fig. 3a. The dimensions of the Bi2223/Ag tape and Bi2223 region were defined in the figure. The equivalent heat current circuits of Bi2223/

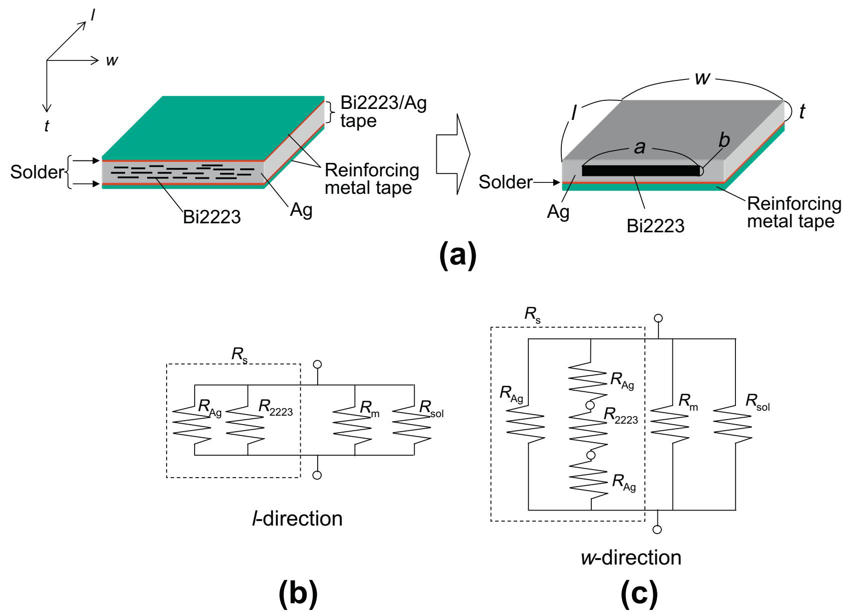

Fig. 3. (a) Schematic image of a model for the equivalent heat current circuit. The dimensions of the tape and the virtually collected Bi2223 region are illustrated. The equivalent heat current circuit for (b) the *l*-direction and (c) the *w*-direction. R_s surrounded by the broken line, R_{Ag}, R_{2223}, R_m and R_{sol} are the thermal resistances of the Bi2223/Ag tape, the Ag region, the Bi2223 filaments, the reinforcing metal and the solder, respectively.

Table 1
Ratio of the amount of the heat-flow among the Ag, reinforcing material and solder layer for the *l*- and *w*-directions of Types HT-SS and HT-CA tapes at 100 K.

	Type HT-SS			Type HT-CA		
	Ag (%)	SS (%)	Solder layer (%)	Ag (%)	CA (%)	Solder layer (%)
l-direction	95	1	4	59	38	3
w-direction	92	1	7	62	31	7

Table 2
Absolute value of the thermal conductivity at 77 K, $\kappa_{abs}(77\ K)$ along the *l*- and *w*-directions for Types H [5], HT-SS and HT-CA tapes.

	$\kappa_{abs}(77\ K)$ (W m^{-1} K^{-1})		
	Type H	Type HT-SS	Type HT-CA
l-direction	240	174	206
w-direction	220	140	206

Ag, R_s's, along the *l*- and *w*-directions, respectively, are shown in Figs. 3b and c. Here, R_s surrounded by the broken line, R_{Ag}, R_{2223}, R_m and R_{sol} are the thermal resistances, $R = (L/\kappa S)$, of the Bi2223/Ag tape, the Ag region, the Bi2223 filaments, the reinforcing metal and the solder, respectively. Using the thermal conductivity of Ag and Bi2223, κ_{Ag} and κ_{2223}, κ of the Bi2223/Ag tape along the *l*-direction, $\kappa_s^{(l)}$, can be calculated by the following relation,

$$\kappa_s^{(l)} = \kappa_{Ag} \times \left(1 - \frac{ab}{wt}\right) + \kappa_{2223} \times \left(\frac{ab}{wt}\right).$$

Since the absolute value of κ_{2223} [8] is known to be about two orders of magnitude smaller than that of κ_{Ag}, κ_{2223} can be ignored. The measured $\kappa(T)$ of both *l*-samples is well reproduced by the calculated κ, κ_{cal}, using the equivalent heat current circuit shown in Fig. 3b, except for around the peak structure at low-temperature, as demonstrated in Fig. 2. The obtained (ab/wt) values, which correspond to the filling factor of the superconducting tape, f_s, are 0.48 and 0.51 for the Types HT-SS and HT-CA samples, respectively. The f_s is defined as the ratio of the volume of the Bi2223 filaments with the Bi2223/Ag tape, V_{2223}/V_s. The f_s value of the Bi2223/Ag tape used here was estimated to be approximately 0.36 from the picture of the cross section [2]. The difference in f_s between the fitting results and the actual value indicates that the small amount of Ag, about 12–15% of total Ag region, does not act as the heat path. For Type HT-SS, the ratio of the amount of the heat-flow among the Ag, SS and solder parts at 100 K is estimated to be approximately 95:1:4, meaning that most of the applied heat flows through the Ag region. On the other hand, the ratio for Type HT-CA is 59:38:3. Therefore, we cannot ignore the contribution of the CA region to the thermal transport, which originates from the high thermal conductive CA. For the *w*-direction, the thermal conductivity of the Bi2223/Ag, $\kappa_s^{(w)}$, can be written as

$$\kappa_s^{(w)} = \kappa_{Ag}(T) \times \left(1 - \frac{b}{t}\right),$$

because of $\kappa_{Ag} \gg \kappa_{2223}$. The similar analysis was done for $\kappa(T)$ of the *w*-samples for both Types HT-SS and HT-CA. The obtained b/t value for Type HT-SS is 0.54 and that for Type HT-CA is 0.51, the values of which are quite similar to the ab/wt values determined independently by the analysis for the *l*-direction. The b/t value represents the cross sectional ratio of Bi2223 region to the Bi2223/Ag tape, S_{2223}/S_s, and then corresponds to the filling factor. The good agreement between the ab/wt and b/t values suggests that the nature of heat transport of the *w*-direction is nearly the same as that of the *l*-direction. For the *w*-samples, the ratio of the amount of the heat-flow among the Ag, reinforcing material and solder parts at 100 K are estimated approximately 92:1:7 for the Type HT-SS and 62:31:7 for the Type HT-CA. These ratios are comparable with those for the *l*-direction, which also supports the conclusion above. The percentage of the contribution of each constitutional part to the heat transport is summarized in Table 1.

The absolute values of $\kappa(T)$ at 77 K, κ_{abs} (77 K), along the *l*- and *w*-directions for Type HT-SS are 174 and 140 W m^{-1} K^{-1} and those for Type HT-CA are 206 and 206 W m^{-1} K^{-1}, respectively. κ_{abs} (77 K) along the *l*- and *w*-directions for the standard Type H were about 240 and 220 W m^{-1} K^{-1}, respectively [5]. The $\kappa(T)$ values of the Type HT series are smaller than that of the Type H tape, which is caused by the low thermal conductive reinforcing metal in comparison with the silver sheath. The obtained results are summarized in Table 2.

5. Summary

We have determined the temperature dependence of thermal conductivity, $\kappa(T)$, of a Bi2223/Ag tape sandwiched by two kinds of thin alloy tapes (stainless steel (SS) or copper-based alloy (CA)) along the length (*l*) and width (*w*) directions. $\kappa(T)$ along the *l*-direction was directly measured using the single sandwiched Bi2223/Ag tape. To obtain $\kappa(T)$ along the *w*-direction, we prepared a stacked bundle in which several sandwiched Bi2223/Ag tapes were soldered. $\kappa(T)$ along both *l*- and *w*-directions are nearly identical with each other, however the pronounced peak structure observed in the *l*-direction was strongly suppressed in the *w*-direction. The calculated $\kappa(T)$ using the equivalent heat current circuit reproduced the measured $\kappa(T)$ successfully. In the Bi2223/Ag-SS, about 90–95% of the applied heat flew through the silver sheath and the contribution of the stainless steel to the thermal transport was negligibly small. On the other hand, the amount of the heat-flow in the copper-based alloy was estimated to be approximately 30–40% of the total applied heat in the Bi2223/Ag-CA. The absolute value of $\kappa(T)$ for the Bi2223/Ag-SS and Bi2223/Ag-CA tapes were approximately 30–40% and 10–15% smaller than that of the standard Bi2223/Ag tape.

References

[1] S. Yamade, N. Ayai, J. Fujikami, S. Kobayashi, E. Ueno, K. Yamazaki, M. Kikuchi, T. Kato, K. Hayashi, K. Sato, H. Kitaguchi, J. Shimoyama, Physica C 463–465 (2007) 821;
G. Osabe, N. Ayai, M. Kikuchi, K. Tatamidani, T. Nakashima, J. Fujikami, T. Kagiyama, K. Yamazaki, S. Yamade, E. Shizuya, S. Kobayashi, K. Hayashi, K. Sato, J. Shimoyama, H. Kitaguchi, H. Kumakura, Physica C 470 (2010) 1365.

[2] T. Naito, H. Fujishiro, Y. Yamada, Cryogenics 49 (2009) 429.

[3] T. Naito, H. Fujishiro, Y. Yamada, IEEE Trans. Appl. Supercond. 19 (2009) 3034.

[4] T. Naito, H. Fujishiro, Y. Yamada, J. Phys.: Conf. Ser. 234 (2010) 022025.

[5] T. Naito, H. Fujishiro, J. Fujikami, IEEE Trans. Appl. Supercond. 21 (2011) 2828.

[6] S. Kobayashi, K. Yamazaki, T. Kato, K. Ohkura, E. Ueno, K. Fujino, J. Fujikami, N. Ayai, M. Kikuchi, K. Hayashi, K. Sato, R. Hata, Physica C 426–431 (2005) 1132.

[7] R.S. Crisp, J. Rungis, Philos. Mag. 22 (1970) 217.

[8] M. Ikebe, H. Fujishiro, T. Naito, K. Noto, J. Phys. Soc. Jpn. 63 (1994) 3107.